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Chapter 28

Designing and maintaining a large closed-system reef exhibit at the Georgia Aquarium

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ABSTRACT

Few large-scale, closed-system living-reef aquariums have ever been built, therefore designing the new living reef exhibit at the Georgia Aquarium faced some difficult challenges. The "South Pacific Barrier Reef" exhibit contains 619,920 L, of which 454,250 L is in the exhibit; the remainder resides in pipes and filters. It is 5.5 m deep, and the viewing window is 14 m wide. The reef is created of fiberglass panels erected on fiberglass scaffolding. Platforms within the fiberglass reef hold 5-metric tons of cultured live rock from Fiji. Water circulation is directed from the bottom of the tank, up through the reef and then to a skimmer box. Pressure-sand filters (silica sand) and foam fractionation with ozone, plus activated carbon, are the primary filtration, with a turnover rate of 60 minutes. Two alternating, variable-drive 14.9 x 10^3 W (20 HP) pumps move water back and forth across the reef face to create additional water motion and turbulence. Lighting is produced by banks of metal halide lamps in conjunction with an overhead skylight that is 40 % transparent to UV light. After two-years the success of the exhibit has been variable. The fishes are in excellent condition. Coral growth at first was quite good, but then declined in late 2006 due to problems with the artificial lighting system and management of water quality parameters. These issues have largely been resolved and coral growth has improved during 2008.

INTRODUCTION

At 51.1 x 10^3 m^2, the Georgia Aquarium is presently the world's largest aquarium. It includes an ocean habitat containing 23.8 x 10^6 L of artificial seawater large enough to maintain four whale sharks; a beluga whale habitat containing 30.3 x 10^5 L of seawater; and 60 other exhibits representing aquatic environments and animals from around the world. Among the featured habitats is a South Pacific coral reef. It is not unusual for aquariums to highlight colorful and exotic animals from coral reefs, but few public aquariums have attempted the challenge and risk of designing and building a living reef on a grand scale.

The principles for maintaining living corals are now well known (Delbeek and Sprung, 1994; Fossa and Nilsen, 1996; Carlson, 1999; Borneman, 2001; Calfo, 2007; Delbeek and Sprung, 2005). Hobbyists and public aquariums around the world have successfully managed small reef aquariums for several decades. The same principles for maintaining water quality, lighting, water motion and other parameters apply to large-scale reef aquariums, as they do with small-scale reefs. However, nearly all of the equipment, lighting and procedures for managing reef aquariums are designed for small systems, and scaling up presents challenges.

The purpose of this paper is to review the process by which the Georgia Aquarium developed its large living reef exhibit, and how some of the design challenges were overcome. At the time this paper was written, the system has been operating for 2.5 years and a summary of the results during this period will be presented. Other aquariums in the future that contemplate creating a large, living reef exhibit should benefit from the experiences presented in this paper.

CONCEPTUAL PLANNING AND DESIGN (2002 – 2004)

Conceptual planning for the Georgia Aquarium commenced in February 2002. During the subsequent months, the mission of the Aquarium was established and the broad outlines of the entire aquarium and its feature exhibits were identified. The exhibits were arranged in thematic galleries focused on freshwater, cold and temperate water environments, the Georgia coast, the open ocean, and on coral reefs. The coral reef gallery (which would eventually be named the "Tropical Diver" gallery) would be centered on a major living reef exhibit. A Pacific coral reef theme was selected because large exhibits of Pacific reef animals are uncommon among public aquariums in the south-eastern United States and therefore would be especially interesting to aquarium guests, and also due to the availability of cultured Pacific reef corals.

To facilitate the design process, a planning workshop was held in January 2003 with invitees representing a broad spectrum of experience covering coral husbandry techniques, life supports systems for coral reef aquariums, aquarium systems developed by hobbyists, and larger aquarium systems in public aquariums. The participants included Anthony Calfo, Mitch Carl (Omaha Zoo), Charles Delbeek (Waikiki Aquarium), Bart Shepherd (Steinhart Aquarium), Julian Sprung, and Joe Yaiullo (Atlantis Marine World Aquarium). Among the challenges discussed during the workshop were these issues:

1. What overall design would work best to display living corals so the public could see and appreciate them?
2. How could live rocks be incorporated into the exhibit?
3. How could sufficient water motion be generated for the corals?
4. What systems, if any, are available to manage calcium and other water quality parameters?
5. What lighting options are available for a large reef exhibit?

The outcome of the workshop, as well as discussions among the Georgia Aquarium design team, resulted in a final design for the coral reef exhibit, as discussed in the following sections.

Overall reef design

Prior to the workshop, the Georgia Aquarium design team decided to simulate a cross section of an entire reef, from a steep reef-wall, to a reef crest where waves crash on the exposed seaward edge, to a calm lagoon and a mangrove swamp. The reef would be modeled after those in the Solomon Islands based on underwater photos and videos. Further, the team decided to develop the underwater and above-water areas of the reef as separate exhibits. The general public would view the reef from underwater, but the topside areas would be developed for school children and others to gain a more complete understanding of how a coral reef system appears in nature.

The architects and exhibit designers established the footprint for the exhibit at approximately 15.2 x 15.2 m, not including additional space for life support systems. The depth of the exhibit was set at 5.5 m. During the January 2003 workshop, the team developed alternative schemes to construct the reef structure, to move water over the reef, to illuminate it, and to incorporate living mangrove trees within the exhibit.

Reef structure and live rocks

The workshop team debated the pros and cons of using live rocks in this large exhibit. Small reefs in home aquariums are comprised entirely of live rocks stacked on top of each other. Some larger reef exhibits, for example at the Atlantis Marine World Aquarium, are constructed from a combination of heavy, quarried base rock with live rock on top. At the Waikiki Aquarium, the reef is constructed of live rocks stacked on top of a fiberglass scaffold. A few aquarists have established reef systems using no live rocks and instead have used fiberglass or other inert materials as a reef foundation.

The plan for the Georgia Aquarium reef was a composite of the various methods for constructing reefs. The base reef would be fabricated from pre-formed fiberglass panels joined together over a scaffolding of fiberglass I-beams. The space behind this fiberglass backdrop would be hollow allowing maximum water volume for the exhibit, and also providing space to hide plumbing.

Scattered across the outer surface of the reef were twelve pockets where live rocks could be inserted. These pockets vaguely resembled “chimneys” in the fiberglass reef. The pockets varied in area from about 1 m^2 to less than half that size. A platform made of fiberglass grating covered with plastic screen formed a platform inside each chimney upon which the live rocks could be placed.

Some concern was expressed that fish might get trapped behind the backdrop since it was hollow. However, reef fish are adapted to seek refuge in caves and recesses within reefs and therefore this was not considered a significant concern. To the contrary, the original plan included provision for sizeable holes to be created in the reef structure to purposely allow fish to swim in and out of the reef and thereby reduce the problem of fish getting “lost” inside the reef.

The Georgia Aquarium made a commitment to preferentially obtain cultured organisms whenever possible. Five metric tons of “cultured” live rocks were ordered two years in advance from Walt Smith Inc. in Fiji in lieu of natural live rocks.

Lastly, concern was expressed that the reef might appear empty on opening day if the corals were small, so artificial corals were included in the exhibit. The initial plan was to remove these artificial corals as the real corals grew in.

The lagoon and mangrove swamp

The reef structure described above was designed to extend vertically about 5.5 m to the surface of the water. From there a concrete reef crest was designed to extend out of the water and over the top of the fiberglass reef structure and form a barrier wall separating the main reef from the shallow lagoon behind it. This wall would have several large openings to allow water and fish to move between the fore-reef and the lagoon, much as they do in nature.

The lagoon was designed to simulate a natural, back-reef habitat typical of Pacific barrier reef and fringing reef environments. The dimensions for the lagoon were set at 14.3 m x 5.1 m, and a water depth of 0.6 m. The bottom would be covered with a layer of coral sand and live rocks. The lagoon was also envisioned as a convenient staging area for depositing live rocks prior to moving them down the reef slope, and it would also become a refuge for fishes and corals that might not be competing well in the deeper reef community on the fore-reef slope. And, in the event of an emergency, the lagoon was designed so that it could be isolated and operated independently of the main reef.

At the rear edge of the lagoon, another wall was designed to contain the mangrove swamp. Since the mangroves had to be planted in mud, the wall had to be solid and impervious to water and nutrients that might leach out of the mud and into the water system for the coral reef. To ensure that this area would remain isolated, the plans called for a plastic liner to be installed inside the concrete basin for the mangroves. The liner would then be weighted down with coral gravel and covered with ordinary potting soil. After the mangroves were planted, the entire swamp would be capped with 15 cm of coral sand to further isolate the mud from the reef water.

Water circulation

Three independent water-circulating systems were designed for the reef exhibit. The life support system (see next section for details) was designed to draw water out of the exhibit via a skimmer located along one side of the lagoon, and also via a bottom drain located along the front edge of the reef at its deepest point. After moving through the filtration system, the water would be returned to the exhibit behind the backdrop through a series of ports located near the bottom of the reef. These ports were directed upwards so that clean water would flow vertically up through the reef (and live rock “chimneys”) and create a positive flow ultimately moving towards the skimmer at the top of the exhibit.

A second water system was designed to create a periodic laminar flow across the reef simulating a back and forth surge action and turbulence similar to that on reefs. Two sets of pumps were located at either end of the exhibit. These “variable drive pumps” pulled water from the far

side of the exhibit: the pumps on the left pulled water from the right side of the exhibit, and vice versa. The intake pipes were located behind the backdrop and the return pipes were located on the front of the reef along each wall. Each of the two vertical return pipes was designed to have four water jets that directed water across the reef face with the first jet opening just below the surface, and the last jet locate just above the bottom of the tank. Both the left wall and the right wall had return jets and they operated sequentially using the variable drive pumps. When the pumps on the left side of the exhibit were on, a strong flow of water moved across the reef from left to right. After running for about a minute, the left side pumps would ramp down and the right side pumps would ramp up creating an opposite flow from right to left across the reef, and then the cycle would repeat.

A third independent system for moving water was designed to operate a wave machine. Ultimately the design team decided to use dump buckets over the top of the reef to create a periodic crashing wave. A series of fiberglass dump buckets that collectively held 22.7 x 10^3 L, would spill onto the reef when the dump bucket tipped over. The dump buckets would all work simultaneously and would be operated by hydraulic pistons using vegetable oil. A timer would provide exact timing for each wave to crash. Water for the dump buckets would be pulled from the exhibit by an independent pumping system.

Life support system

The design for the life support system specified that water removed from the exhibit via the skimmer box and the bottom drain would first flow through two foam fractionators (RK2 Systems, model 2000), each 3.0 m in diameter and 2.4 m tall at a flow rate of 302.8 $m^3.h^{-1}$ through each device. Two-percent ozone would be supplied to foam fractionators at a rate of 0.05 $mg.L^{-1}$ delivering 0.45 $kg.d^{-1}$. From there the water would flow into a de-aeration tower filled with Brentwood media (Brentwood Industries) for gas exchange. A 30 % side-stream from the de-aeration tower would circulate water through twin pressure sand filters (Neptune Benson, model 66SRFFG-6, 2.8 m^3 volume, 2.2 m^2 filter area, flow rate 1.1 $m^3.min^{-1}$, silica sand media). Water from the sand filters would flow back to the de-aeration tower and from there it would gravity feed into the exhibit through the pipes behind the reef. Additional side stream flows were designed to run water through a custom-made 5,700 L calcium reactor designed to hold 1,860 kg of aragonite media (Carib Sea Geo-Marine media) with an outflow rate of 0.004 $m^3.min^{-1}$. A separate side-stream was directed to a custom-made activated carbon filter designed to hold 544 kg of flake carbon (Siemens).

Lighting

A combination of artificial lighting and natural sunlight was incorporated into the final design. The gallery was located on the south side of the building to take advantage of natural sunlight. The architects designed a large 16.8 m x 19.8 m skylight over the exhibit and specified clear glass (Starphire) in the construction. The location of the skylight was not positioned directly over the exhibit but rather it was centered somewhat to the southwest. Computer modeling showing the path of the sun throughout the year indicated that this location would maximize the amount of light entering the exhibit both in the summer and in the winter. In addition, the roof was slanted to face south.

Shallow coral reefs are bathed in intense sunlight, including high ultraviolet radiation (UV). While UV light can be deleterious or lethal, corals produce microsporin-like amino acids that provide protection from UV rays (Dunlap & Chalker 1986). To more closely simulate the natural light conditions on reefs, the glass for the skylight was specified to be transparent to UV light.

The most powerful metal halide lights appropriate for a coral reef exhibit are 2 kW Osram lamps manufactured in Europe. At the time this exhibit was designed, the Steinhart Aquarium was testing these lamps to use on their new large reef exhibit scheduled to open in 2008 (see chapter 29). Unfortunately, the ballast and other electronic components to operate these lamps with U.S. voltage had not been developed and would need to be improvised for use on the new Georgia Aquarium exhibit. The Steinhart Aquarium faced similar challenges and the two institutions collaborated to try to develop a workable solution.

Two additional banks of metal halide lamps were designed on either side of the exhibit and angled down, and across the face of the reef. Each bank consisted of 15 lights, of which 11

were 6,500 K (Sunmaster) and 19 were 14,000 K (Hamilton) (all 1 kW) and they were to be positioned between 2.4 m and 3.0 m above the water surface.

Viewing

The first design for this exhibit called for an ordinary flat viewing window looking on to the reef wall. This allowed visitors to get up close and see the details in the corals, but the space between the window and the reef was narrow and provided limited room for the fishes to swim. To solve this problem, a curved window was designed that arched up and over the visitors. This allowed fishes room to swim in the wide-open surface waters and still allowed visitors to get a close view of the corals in the deeper section of the reef. This also allowed us to simulate a more natural wave that would crash directly over the heads of visitors.

The top level of the exhibit was designated as a learning area for students. A classroom was designed adjacent to the exhibit where students could receive instruction about corals and coral reefs. From there they could walk out and peer into the reef from above and watch as the dump buckets operated creating loud, realistic waves. Farther back, a walkway over the lagoon was designed to permit students to stand over the water and see fishes and corals and also view the mangroves.

Interpretation

With so many species in this exhibit, identification and interpretation using standard graphics panels presented a dilemma. Plastering the wall with photos and text was not an option. Instead, a series of computer kiosks was developed to present a menu of fishes and corals to visitors. By touching an image, instantaneous information and more photos would pop up. Potentially thousands of species could be entered into this interactive computer ID system.

RESULTS (2005 – 2008)

By June 2005, the exhibit was completed and filled with fresh water for testing. On June 15, 2005 dye was added to the system to determine flow patterns (McMaster-Carr Supply Co., catalog no.1400T43, Fluorescent Dye Water Tracer). Despite a 60-minute turnover rate of all the water through the life support system, the return flow produced no detectable currents in the water. All of the water was returned to the exhibit via gravity and entered behind the backdrop. It took two minutes for this water to percolate through the reef structure and begin to flow slowly up through the live rock chimneys. By contrast, the surge pumps propelled water halfway across the reef in 30 seconds and generated a noticeable laminar flow across the exhibit. To date, no quantitative measurements of the flow rate have been made.

The dump buckets generate a realistic wave with great visual effect on those standing beneath it. Despite the volume of water, this wave generates virtually no water motion below 1.0 m depth. It does, however, propagate a small wave that travels across the surface and enters the lagoon. The crashing wave also generates small bubbles that persist in the water and are carried around the exhibit in the currents. Further testing allowed us to determine that the optimal frequency for the wave to crash was once every two minutes. This allowed enough time for most of the bubbles to disperse and also to ensure that most visitors in the gallery had the opportunity to experience the wave crashing at least once during their visit to the exhibit.

An unexpected side benefit of the wave device came about when we searched for ways to disrupt the surface water. During the two minutes when there was no crashing wave, the surface of the water was completely flat allowing visitors below to look up and see all of the fixtures, lights, plumbing and other paraphernalia above the exhibit. To break up the surface, we kept the dump buckets in the down position during the two-minute interval between wave crashes. This constant cascade of water created a small chop on the surface effectively preventing visitors from seeing the lights and other equipment above the water. At the end of the two-minute cycle, the buckets swiveled upright and filled in 20 seconds, then the hydraulic system tipped them over. This timing was so precise that a music score was written rising to a crescendo at the exact moment when the dump buckets tip over.

The live rocks arrived in July 2005 and were immediately introduced into the lagoon after a quick rinse to remove debris and any dead organisms. A few weeks later, the water level was reduced so the mangrove trees could be

planted. The procedure was completed during the week of August 14, 2005, with assistance from Charles Delbeek and Bart Shephard, and afterwards the water was returned to its normal level. No mud leaked into the system.

During that same week, light levels in the exhibit were tested using a LiCor meter loaned to us by our colleague Richard Harker. Despite aiming all of the 2 kW Osram lamps on the various planters, as well as all the sidelights, the minimum PAR readings at a depth of 4.6 m ranged between 200 – 400 μmol.m^{-2}.s^{-1}. This was acceptable, but below our expectations. Over time, the 2 kW fixtures became increasingly undependable and eventually all but four of them failed to ignite. This greatly diminished the light levels through the winter of 2006 and spring of 2007 and probably contributed to the poor growth of corals during those months. To rectify this situation, a new bank of lights was installed directly over the reef. This new bank consists of thirty 6,500 K Sunmaster lamps, all 1 kW, which were gradually turned on and lowered to a height of 1.2 m above the surface. The current lighting regime has the two banks of sidelights turning on by 7:00 am. The thirty overhead lamps come on four-at-a-time starting at 8:00 am with four more coming on every 10 minutes thereafter. This sequence is reversed beginning at 4:30 pm as the lights begin to go out.

Natural sunlight floods the exhibit from April through September from about 10:00 am to 3:00 pm creating a very natural "sunbeam" effect. The artificial lights remain on even during periods of full sunlight. The possibility of turning off the artificial lights during bright sunlit periods was discarded as impractical due to the unpredictability of cloud cover and rain. From October through March, the artificial lights are the only source of lighting for the corals. Ultraviolet light at the surface of the exhibit has been measured using an Apogee UV meter. While the units of measurement are not clearly given for this device (other than stating that it measures UV-A plus UV-B), in relative terms about 40 % of the available UV light enters the exhibit through the skylight compared to outdoor measurements above the skylight.

1,500 fishes representing 70 species were introduced to the exhibit during the September 2005 and continuing through October. All of these fishes were quarantined for at least 45 days prior to their introduction to the exhibit. Most aquarists recognize that the first six weeks is a critical time period for a new reef exhibit. If any outbreaks of fish parasites and diseases are going to appear, they are most likely to happen during this period. Within a month after the first fish were introduced an outbreak of *Cryptocaryon irritans* appeared and mortality spiked. In living reef systems, virtually nothing can be done except to let the disease run its course. Eventually, the outbreak subsided and there has been no significant recurrence. Most of the original fish population recovered and eventually more fish were added over the subsequent months. Since that time, the condition of the fish population has been excellent with the fish showing good coloration, as spawning has been observed for *Pseudanthias squamipinnis* and *Chromis viridis*. A current inventory of fishes in this exhibit is presented in Appendix I.

The fishes selected for this exhibit included a preponderance of herbivores selected to control algal growth. They have succeeded in this regard and there has been no detectable growth of "hair algae" and other macro algae in the exhibit, except for calcareous algae which now covers all of the available surfaces in the exhibit (except the window which is cleaned daily by divers). All of the artificial corals were quickly covered with coralline algae. The original plan was to remove these artificial corals but instead they have remained in the exhibit and now resemble dead corals that naturally occur on a coral reef.

The holes that were intended to allow fishes to swim in and out of the reef structure were smaller in size and fewer in number than originally planned. As a result, fishes occasionally found their way behind the reef and then never re-emerged. They have remained permanent residents behind the backdrop. Food is provided to them separately from the general population of fishes.

Living corals were introduced to the reef during September 2005. These corals were obtained as donations from other public aquariums and some were received as confiscations from U.S. Customs and the U.S. Department of Agriculture. 753 fragments representing 200 species of corals were introduced into the exhibit (Appendix II). Mortality was low initially but gradually many of the acroporid species showed signs of necrosis and died. However, other *Acropora* spp. have

persisted but actual growth rates have not been quantified. Nonetheless, from photographs it is apparent that most of the acroporids have not flourished and are only growing slowly. Soft corals, including *Sarcophyton*, *Xenia*, and *Rumphella* appear to be thriving, as is a fire coral *Millepora* sp.

Water quality

Maintaining stable water quality parameters has been challenging and has also contributed to the problems with the corals. “Instant Ocean” brand sea salt was selected for this exhibit and it is mixed with tap water purified through a reverse osmosis (RO) system. The evaporation rate varies from about 1,100 – 1,900 L per day depending on temperature and humidity of the overlying air. This is replaced with RO water.

Water quality samples are taken daily for pH, salinity, dissolved oxygen, alkalinity and calcium concentration, every other day for phosphate and weekly for ammonium, nitrite, nitrate, strontium and iodide. pH and salinity are measured with standard laboratory probes, alkalinity is calculated from pH titrations with dilute HCl. Dissolved oxygen was initially measured with membrane cell probes (YSI Inc.) but switched to fluorescent LDO (Hach Company) during early 2007. Ammonium, nitrate and nitrate were initially measured using Hach pillow chemistries read on DR890 colorimeters, but reading later switched to a Hach DR5000 spectrophotometer. Calcium, Strontium, Iodide and Magnesium were initially measured using SeaChem wet chemistry titration kit (SeaChem). Since early 2007 all cations and anions have been analyzed by direct separation on a Dionex ICS-3000 reagent-free ion chromatograph, using cation and anion column configurations with conductivity and electrochemical detection, as needed.

Nitrate *(Figure 1)*

Nitrate has risen gradually in the exhibit, but perhaps not as fast as might be expected given the bioload and feeding rate (about 2.0 kg twice per day consisting of rotifers, krill, mysids, cyclops, brine shrimp, blood worms, clams, fish, shrimp, and squid, plus bunches of romaine lettuce). Given the amount of live rock and surface area, a certain amount of natural denitrification probably takes place in the exhibit. The system does not presently have a dedicated denitrification unit in the life support design, but that capacity exists and may be installed at a later date, should the nitrate accumulation become worrisome.

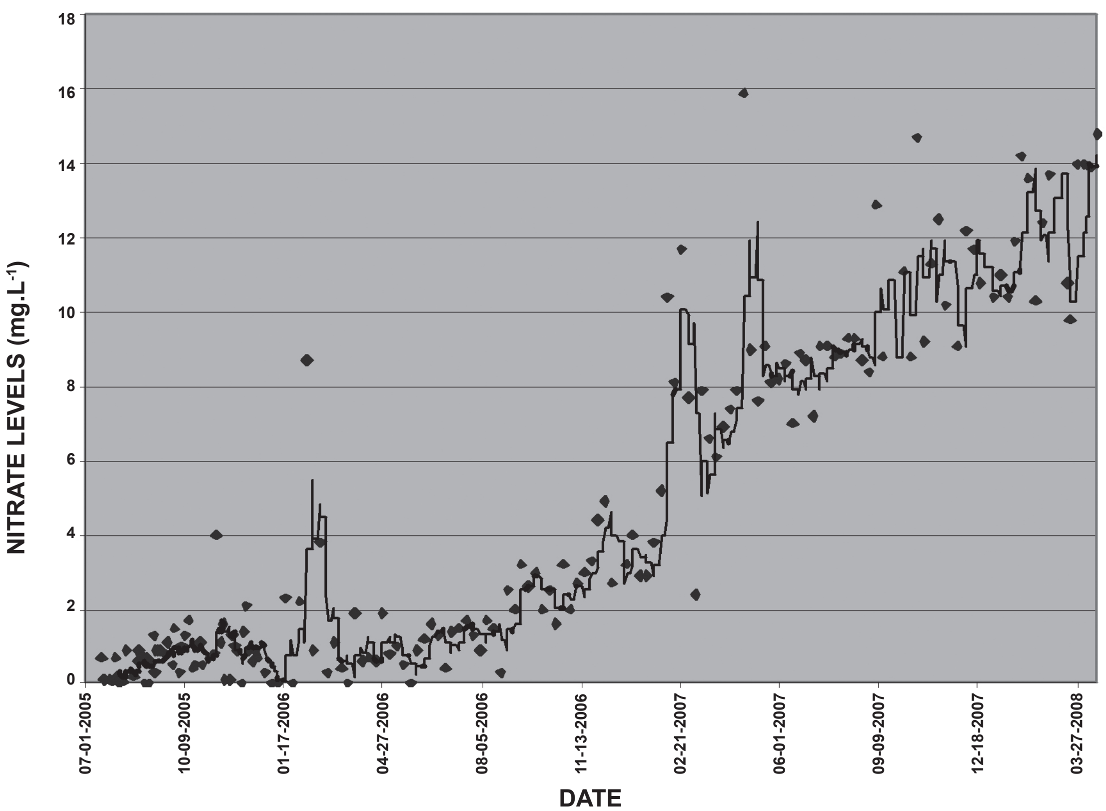

Figure 1. Nitrate (NO_3 – N) levels in the Pacific Barrier Reef exhibit from July 2005 to March 2008

pH *(Figure 2)*
The pH has remained fairly steady in the 8.2-8.3 range except for a period in early 2007 when calcium hydroxide was added daily (1,250 -2,500 g.d^{-1}) over approximately a month to correct declining calcium concentrations (Figure 2). This pushed pH above 8.45 for a time before the additions were terminated.

Phosphate *(Figure 3)*
Phosphate accumulated fairly steadily until July 2007 when a calcium reactor was added

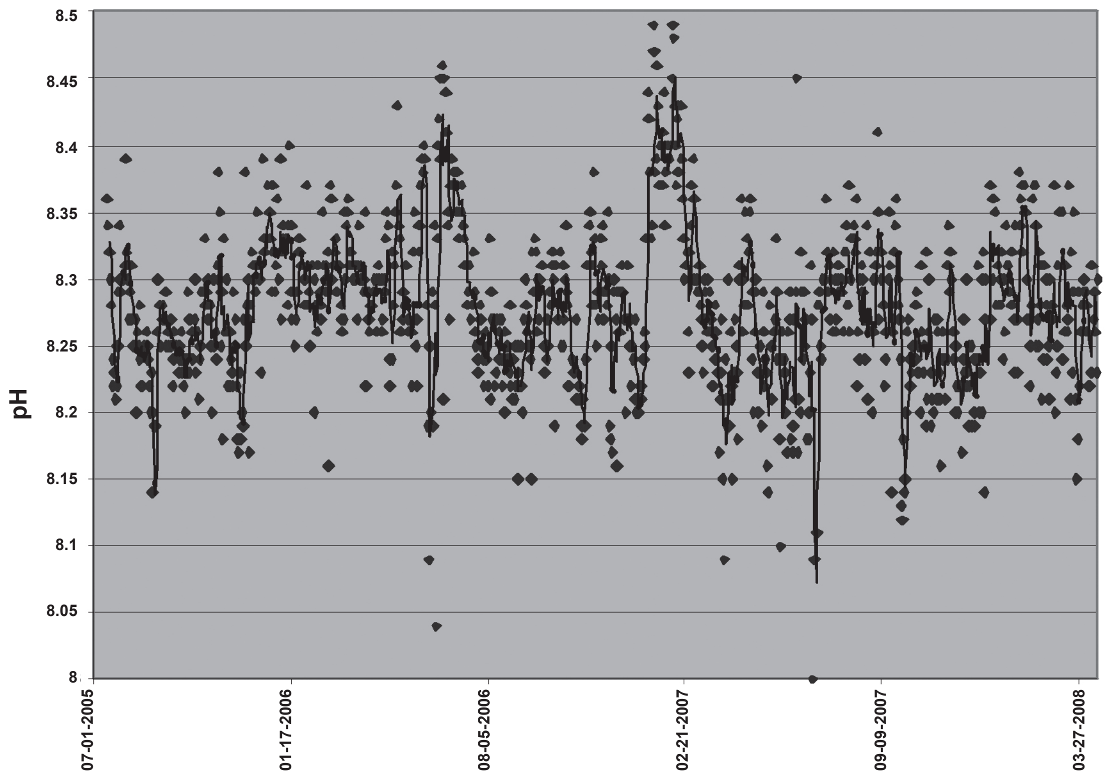

Figure 2. pH in the Pacific Barrier Reef Exhibit from July 2005 to March 2008

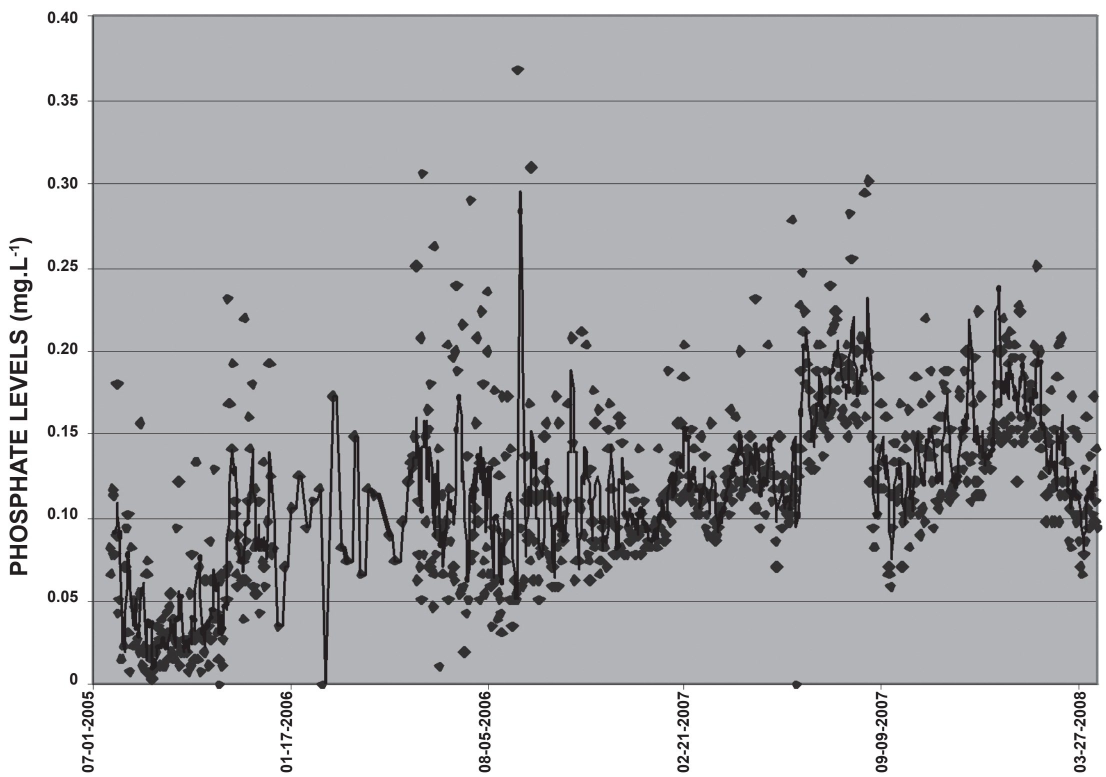

Figure 3. Phosphate (PO_4-P) in the Pacific Barrier Reef Exhibit from July 2005 to March 2008

to the life support system. This resulted in an increase in the rate at which phosphate was accumulating in the exhibit, almost certainly due to liberation of phosphate ions upon dissolution of the calcareous media in the calcium reactor. In September 2007 a custom-made 22 L phosphate reactor containing 4 kg of pelletized ferric oxide ("Bayoxide E33P"), with a flow rate of 0.004 $m^3.h^{-1}$, was added to the system, which resulted in an immediate dip in phosphate concentration. The increasing trend persists however, so

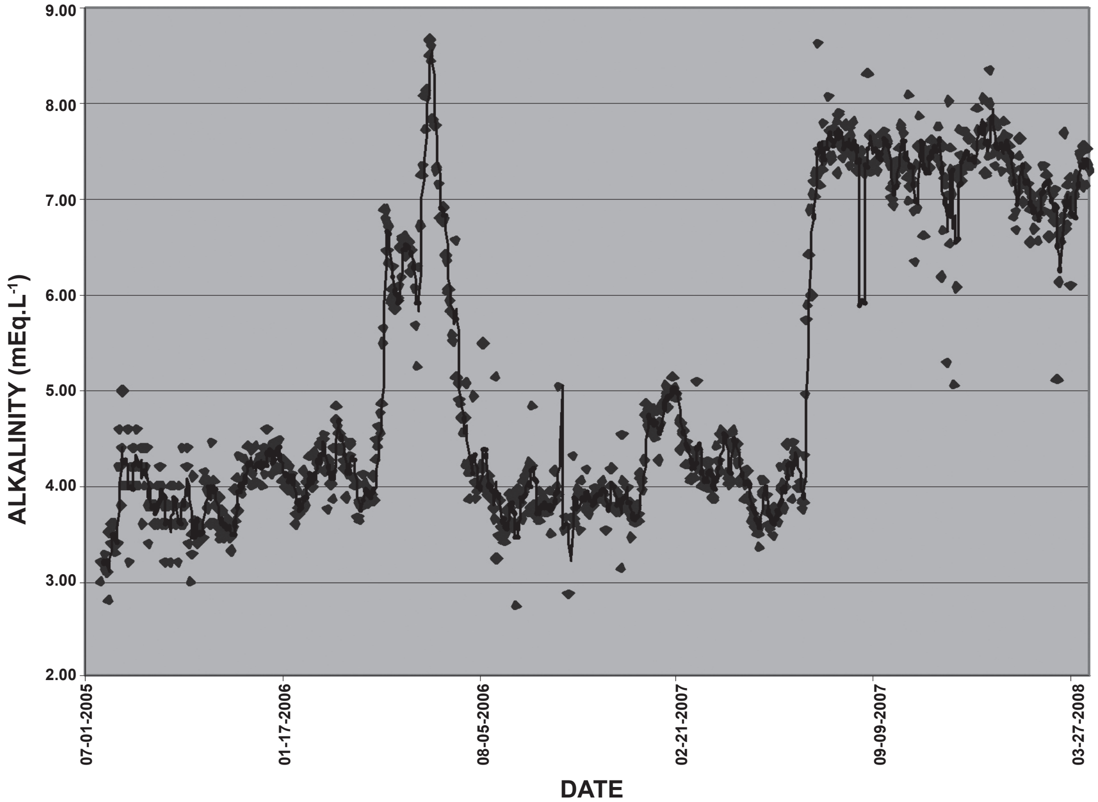

Figure 4. Alkalinity (mEq.L^{-1}) in the Pacific Barrier Reef exhibit from July 2005 to March 2008.

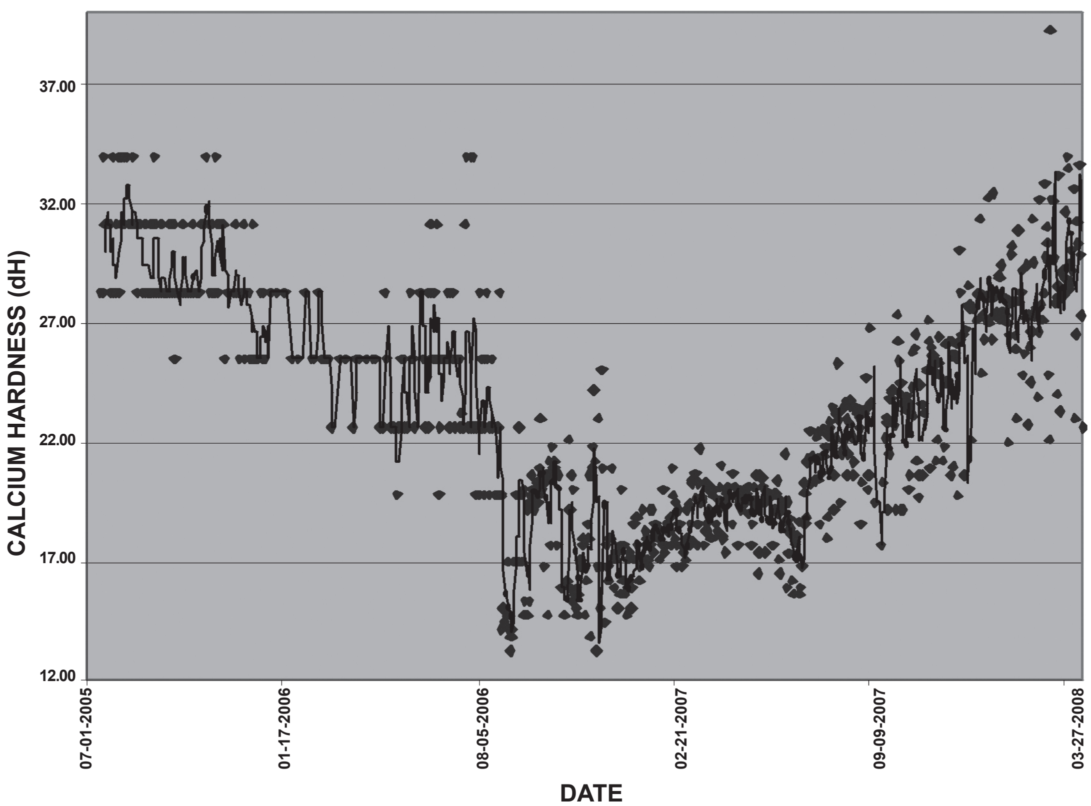

Figure 5. Calcium hardness (dH) in the Pacific Barrier Reef exhibit from July 2005 to March 2008.

management of phosphate using lanthanum chloride additions is likely to be instituted in the near future. These additions would be made on the intake side of one of the sand filters, such that precipitated lanthanum phosphate would be removed from the system during the next scheduled backwash.

Alkalinity *(Figure 4)*
Alkalinity has been quite dynamic in the exhibit, mostly due to additions and modifications to the life support system. The early spike in June 2006 was a direct result of calcium hydroxide additions. These additions were ceased when calcium concentration reached desired levels and concern was raised over the increasing alkalinity. The more recent increase through July 2007 resulted from the installation of a calcium reactor.

Calcium *(Figure 5)*
Calcium dynamics have been similar to alkalinity, for the same reasons. An early spike resulted from calcium hydroxide additions (see comments above on pH). Unfortunately, measurement error was higher during that time due to the use of a different analytical method. Nonetheless, the 5-period moving average shows the high early value. Active calcification by crustose coralline algae and hermatypic corals resulted in net reductions of dissolved calcium. Recent increases since July 2007 are a result of the installation of the calcium reactor. Calcium concentration continues to increase in the exhibit and we are now measuring sustained concentrations above the target level of 25.4 dH.

CONCLUSIONS

The Georgia Aquarium's Pacific Barrier Reef exhibit is one of a new generation of large, living-reef exhibits. Each of these exhibits has pioneered new technologies and exhibit designs. Despite some failures and set-backs, our experiences have helped improve our knowledge of how to create successful large environments for maintaining living corals and reef fishes. The Georgia Aquarium believes that accurately reporting the difficulties and set-backs are as important as the successes in order to help advance our collective understanding of these living systems.

During the first two years of operation, the Georgia Aquarium's Pacific Barrier Reef exhibit has proven to be a popular exhibit for guests (Figure 6). The colorful fishes, the natural sunlight during the summer months, the overhead crashing wave, and the unique window design all combine to create a memorable experience for visitors. The large fish population has been stable and healthy after an early outbreak of disease during the first six weeks.

The two young blacktip reef sharks, *Carcharhinus melanopterus,* introduced into the reef exhibited behavior similar to that observed in the wild. During the day they resided in the shallow lagoon water and at night moved across the reef crest into the deeper reef water. However, this behavior was undesirable from an exhibit perspective. They could not be seen by visitors in the daytime, and they were disruptive in the lagoon constantly knocking over corals in the shallow water. To keep the sharks on the deep side of the reef, a barrier of live rocks was placed in the channel between lagoon and the main reef. This barrier prevented the sharks from moving into the lagoon, but smaller reef fishes could continue to move back and forth through the small openings between the rocks.

During the design phase, the mud in the planter box for the mangrove trees was perceived as a possible source of water contamination. However, the cap of coral sand over the mud appears to be working to prevent direct exposure of the mud with the overlying water. The mangrove trees are growing well, although the larger trees did not acclimate as well as the small trees and saplings. Our recommendation, based on this experience would be to obtain seedlings or very small trees under 1m in height. To date, leaves falling from the trees have not been a significant problem in the overflow skimmer.

The artificial corals fulfilled their role during the opening weeks of the new exhibit making the exhibit appear much like a mature coral reef. However, during the subsequent months a succession of algal species covered the corals, ultimately reaching a state where they have all been covered with coralline algae. These artificial corals have not been removed from the exhibit, as originally planned, because they now appear like dead corals that would normally be found on any coral reef. Further, they now provide additional surface area for planting living corals.

Lighting the reef continues to be a challenge. All of the 2 kW fixtures ultimately failed and were removed. The new bank of lights directly over the exhibit is now in operation and conclusions about their effectiveness will not be known for some time. During the winter months of 2007-2008, these lights provided the principal source of lighting for the reef slope. During the summer months, natural sunlight is abundant and provides near-natural levels of light for the corals, as well as a very pleasant aesthetic effect for viewing. Cleaning

A

B

Figure 6: Two views of the Pacific Barrier Reef exhibit. A) above-water view of the reef slope and lagoon, and the observation area for students, B) the public viewing area under the main window with an overhead crashing wave.

the skylights is a maintenance issue that must be addressed. City dust and soot continually settles on the glass blocking light. The reduction in light levels has not yet been measured but to minimize this effect the skylights are washed at least twice each year, in the spring and in the fall.

The record of coral growth and survival in the system has been mixed. Initially, when the water quality parameters were near normal, the corals were thriving and growing. The 2 kW lights were also functioning during the early months. But as the water quality parameters declined and as the 2 kW lamps failed, the corals also declined in vigor and mortality increased. It remains to be seen if the improved techniques for managing water quality, combined with better lighting will result in better coral growth and survival – particularly among the acroporid corals. Additionally, improvements to the water surge system will be tested to increase water flow across the reef, perhaps by lengthening the amount of time the pumps remain on for each surge, or by installing eductors or other methods to increase flow.

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APPENDIX I: Inventory of fishes in the Pacific Barrier Reef exhibit at the Georgia Aquarium as of November 2007.

Genus	Species	#	Genus	Species	#
Acanthurus	*achilles*	16	*Labroides*	*phthirophagus*	10
Acanthurus	*dussumieri*	7	*Meiacanthus*	*oualanensis*	2
Acanthurus	*nigricans*	4	*Naso*	*lituratus*	11
Acanthurus	*olivaceus*	21	*Naso*	*unicornis*	6
Acanthurus	*pyroferus*	6	*Naso*	*vlamingi*	6
Acanthurus	*triostegus*	10	*Nemateleotris*	*magnifica*	5
Amphiprion	sp.	2	*Neocirrhites*	*armatus*	6
Apogon	*amboinensis*	1	*Odonus*	*niger*	1
Apogon	*cyanosoma*	7	*Oxycirrhites*	*typus*	3
Apogon	*cyanosoma*	1	*Paracanthurus*	*hepatus*	60
Apogon	*maculatus*	5	*Paracheilinus*	*carpenteri*	1
Apogon	*menesemus*	27	*Paracirrhites*	*arcatus*	5
Apogon	sp.	45	*Paracirrhites*	*forsteri*	1
Bodianus	*anthioides*	1	*Paraluteres*	*prionurus*	3
Bodianus	*axillaris*	1	*Platax*	*teira*	7
Caesio	*teres*	20	*Plectorhinchus*	*chaetodonoides*	2
Canthigaster	*valentini*	2	*Plectorhinchus*	*lineatus*	5
Carcharhinus	*melanopterus*	2	*Pomacentrus*	*moluccensis*	6
Centropyge	*bicolor*	3	*Pseudanthias*	*bimaculatus*	7
Centropyge	*bispinosa*	1	*Pseudanthias*	*hutchii*	2
Centropyge	*flavissimus*	3	*Pseudanthias*	*hypselosoma*	5
Centropyge	*loricula*	2	*Pseudanthias*	*pictilis*	5
Chaetodon	*lunula*	3	*Pseudanthias*	*pleurotaenia*	30
Chiloscyllium	*punctatum*	4	*Pseudanthias*	*squaminpinnis*	130
Chiloscyllium	*plagiosum*	4	*Pseudocheilinus*	*hexataenia*	2
Chromis	*viridis*	41	*Pseudochromis*	*fuscus*	2
Chrysiptera	*cyanea*	52	*Ptereleotris*	*zebra*	7
Cirrhilabrus	*cyanopleura*	3	*Rhinecanthus*	*rectangulus*	1
Cirrhilabrus	*exquisitus*	4	*Salarias*	*fasciatus*	2
Cirrhilabrus	*rubriventralis*	4	*Scolopsis*	*bilineata*	7
Cirrhilabrus	*scottorum*	5	*Siganus*	*doliatus*	8
Coris	*gaimard*	2	*Siganus*	*doliatus*	11
Cryptocentrus	*leptocephalus*	2	*Siganus*	*puellus*	3
Cryptocentrus	*pavoninoides*	2	*Siganus*	*vulpinus*	16
Ctenochaetus	*striatus*	8	*Sphaeramia*	*nematoptera*	82
Ctenochaetus	*strigosus*	8	*Synchiropus*	*ocellatus*	2
Cyprinocirrhites	*polyactis*	1	*Thalassoma*	*duperrey*	1
Dascyllus	*auripinnis*	13	*Thalassoma*	*lunare*	1
Dascyllus	*melanurus*	11	*Valenciennea*	*strigata*	4
Ecsenius	*midas*	4	*Valenciennea*	*strigata*	5
Genicanthus	*lamarck*	6	*Zanclus*	*canescens*	7
Genicanthus	*melanospilos*	1	*Zebrasoma*	*flavescens*	555
Gomphosus	*varius*	2	*Zebrasoma*	*scopas*	10
Hemitaurichthys	*poylepis*	22	*Zebrasoma*	*veliferum*	40
			Total		**1474**

APPENDIX II: Inventory of cnidarians and Tridacna introduced into the Pacific Barrier Reef exhibit at the Georgia Aquarium through November 2007.

Genus	Species	#	Genus	Species	#
Acropora	*accuminata*	42	*Euphyllia*	*divisa*	
Acropora	*efflorescens*	2	*Euphyllia*	*paradivisa*	1
Acropora	*austera*	3	*Clavularia*	sp.	2
Acropora	*elsyi*	11	*Turbinaria*	*reniformis*	3
Acropora	*microphthalma*	22	*Turbinaria*	*peltata*	6
Acropora	*millepora*	18	*Rhodactis*	sp.	1
Acropora	*formosa*	20	*Caulastrea*	*furcata*	6
Acropora	*nana*	54	*Caulastrea*	*echinulata*	22
Acropora	*nobilis*	26	*Favia*	sp.	15
Acropora	*pulchra*	27	*Platygyra*	*lamellina*	1
Acropora	*robusta*	1	*Herpolitha*	sp.	1
Acropora	sp.	58	*Fungia*	sp.	1
Acropora	*tenuis*	4	*Rumphella*	sp.	1
Acropora	*valencienna*	3	*Heliopora*	*coerulea*	1
Acropora	*yongei*	102	*Merulina*	*sp.*	2
Montipora	*aeqituberculata*	5	*Hydnophora*	*rigida*	30
Montipora	*capricornis*	6	*Hydnophora*	sp.	3
Montipora	*confusa/spumosa*	3	*Hydnophora*	*exesa*	2
Montipora	*digitata*	40	*Hydnophora*	*rigida*	6
Pavona	*cactus*	6	*Hydnophora*	sp.	3
Pachyseris	sp.	1	*Symphyllia*	sp.	1
Pachyseris	*speciosa*	1	*Cynarina*	*lacrymalis*	3
Erythropodium	*caribaeorum*	1	*Lobophyllia*	*hemprichii*	6
Cladiella	sp.	3	*Lobophytum*	sp.	3
Klyxum	spp. 2	2	*Galaxea*	*fascicularis*	2
Sarcophyton	sp.	2	*Pocillopora*	*damicornis*	19
Sarcophyton	sp.	2	*Seriatopora*	*hystrix*	1
Sarcophyton	sp.	24	*Stylophora*	*pistillata*	1
Sinularia	sp.	13	*Porites*	sp.	3
Sinularia	*polydactyla*	1	*Trachyphyllia*	*geoffroyi*	36
Briarium	sp. 1	5	*Tridacna*	*derasa*	3
Euphyllia	*glabrescens*	5	*Xenia*	sp.	15
Euphyllia	*ancora*	4	*Zooanthus*	*pulchellua*	1
Euphyllia	*parancora*	11	**Total**		**753**